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SOIL FUMIGATION FOR PLANT DISEASE CONTROL

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The control of soil-borne plant diseases by soil fumigation has been shown to be efficient and practicable in greenhouses, seed beds, cold frames, small gardens, and for certain crops in the field. Any method of soil sterilization is expensive. Therefore, soil fumigation is ordinarily used only for those crops that are valuable enough to justify a fairly high cost of production.

The root-knot nematode, root-lesion nematode, tomato wilt fungus, southern blight fungus, damping-off fungi, and weeds usually were controlled in soils fumigated with chloropicrin at rates of 2.5 to 4 milliliters per cubic foot (400 to 600 pounds per acre). The root-knot nematode generally was controlled in soil fumigated with carbon disulphide at rates of 1000 to 3000 pounds per acre; with methyl bromide at 165 to 300 pounds per acre; and with pentachlorethane or tetrachlorethane at 2000 pounds per acre. Less satisfactory results were secured with xylene, ethylene dichloride, sodium cyanide and formaldehyde.

Paper impregnated with hoof-and-horn glue, casein glue, or vegetable paste, and adequately sealed at the edges, was most satisfactory for confining chloropicrin and carbon disulphide in the soil. However, good results were secured with these chemicals when the fumigated soil was covered with Sisalkraft, asphalt-coated paper, or when the surface of the soil was kept wet. Low concentrations of the fumigants were effective when the fumigants were tightly confined in the soil.

Soil fumigation boxes, made gas-tight by glueing the boards together and sealing the cover, were very effective for confining fumigants to kill plant-disease fungi and other pests in potting soils.

Detailed directions for the fumigation method of soil sterilization are given together with an outline of the necessary precautions.

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SOIL FUMIGATION FOR PLANT-DISEASE CONTROL[a]

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Under natural conditions, soil that is used for growing cultivated plants is inhabited by many forms of plant and animal life. Most of these are beneficial, such as the nitrifying bacteria, humus-decaying organisms, and earthworms. In the same soil destructive organisms are also commonly present including certain fungi, bacteria, and nematodes that cause plant diseases. Undesirable weeds are also frequently present.

This bulletin deals with soil fumigation designed especially to control these disease-producing organisms that infest the soil. It is based on experiments conducted in the last seven years at the Tomato Disease Laboratory at Jacksonville, Texas, and in the last four years at the Lower Rio Grande Valley substation at Weslaco, Texas. Also, a compilation is presented of data gathered from all available sources on preferred methods of soil sterilization by fumigation.

Soil sterilization for the control of various soil-borne organisms detrimental to plants has been practiced for many years. The root-knot nematode, *Heterodera marioni* (Cornu) Goodey, probably is the most destructive soil-inhabiting plant pest that has been combated in this way (3, 68) [b]. In the South, the root-knot disease caused by this nematode affects a wide range of plants in fields, nurseries, and home gardens (68). In northern states, it is serious in greenhouses. The root-lesion (or meadow) nematode, *Pratylenchus pratensis* (de Man) Filipjev, has been reported on an increasingly wide range of plants, and occasionally is serious in nurseries and fields. The bulb and stem nematode, *Ditylenchus dipsaci* (Kuehn) Filipjev, also is largely soil-borne, and several other species of nematodes cause damage to special crops. The sugar beet nematode *(Heterodera schachtii)* is another destructive species. Many kinds of soil fungi and bacteria cause root decay, wilting, and other signs of plant injury; others cause damping-off of seedlings and young plants. Persistent weeds such as nutgrass *(Cyperus rotundus* L.), Johnson grass *(Sorghum halepense* (L.) Pers.), crab grass *(Digitaria sanguinalis* (L. Scop.), and others, many of which have deep underground stems and rhizomes that make weeding by cultivation ineffective, are frequent obstacles in plant culture. All of these many soil-inhabiting pests may be controlled by soil fumigation.

Various methods of soil sterilization have been used. Heat was probably first employed by burning brush or straw on the surface of the ground. As this treatment did not penetrate deeply enough into the soil, methods of applying live steam and drenching with hot water were developed and

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[a]Acknowledgment is made of certain materials and applicators that were furnished for this work by Innis, Speiden & Co., New York City; Freeport Sulphur Co., New York City; R. & H. Chemicals Dept. of E. I. du Pont de Nemours Co., Niagara Falls, N. Y.; Dow Chemical Co., Midland, Mich.; and Thompson-Hayward Chemical Co., Houston, Texas.

[b]Numbers in parentheses refer to Literature Cited.

both of these methods are still used commercially (44, 56, 30). Recently, heat sterilization by means of a system of electrically heated units in the plant bed or soil box has been developed.

Liquid soil drenches with disinfecting chemicals such as mercuric chloride, formaldehyde, various organic mercury compounds, cyanide compounds, sulphuric and other acids, and emulsions of chloropicrin and carbon disulphide, all have merit for specific purposes and are used extensively (25).

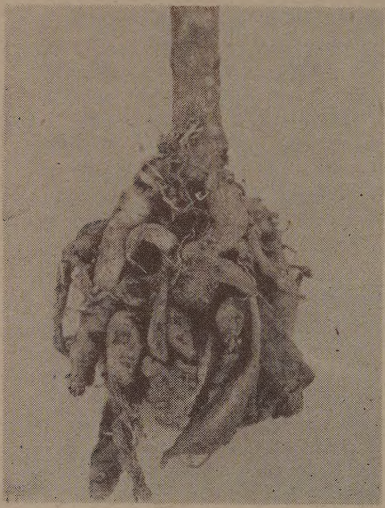

Figure 1. Tomato root-knot caused by the nematode, *Heterodera marioni.* Large fleshy galls of this type are frequently produced by the root-knot nematode on many herbaceous plants, such as beans, tomatoes and watermelons.

All soil drench treatments require large amounts of water, however, for adequate distribution of the sterilizing agent through the soil, and a long period for drying of the soil is required before planting. Surface applications of cuprous oxide, organic mercury compounds, and zinc oxide to the soil are used to control damping-off fungi (70).

Soil sterilization by fumigation has a distinct advantage in that only relatively small quantities of the chemical need be applied, as contact with the soil organisms is obtained by diffusion of the gas. Furthermore the soil may be planted within a few days after treatment. Hydrocyanic-acid gas, carbon disulphide, chloropicrin, ethylene dichloride, methyl bromide, and paradichlorobenzene are the most important chemicals used for soil fumigation. All of these compounds produce gas immediately after application, and penetrate the soil thoroughly from the points of application (18, 22, 52).

Much of the early literature on chloropicrin was concerned with its manufacture, physico-chemical properties, and possible uses for plant pest control (32, 47, and 48). Chloropicrin did not become valuable as a soil fumigant until adequate methods were developed for confining it

in the soil. The most efficient practical method found consisted in covering of the soil with paper bearing a gas-confining coating of hoof-and-horn glue, casein glue, or vegetable paste (17, 23, 72). A cheaper, easier but less dependable method was the use of the wet-soil seal (water seal) for confining gases that are insoluble in water (72).

Soil fumigation with chloropicrin has been especially useful in controlling root-knot nematodes (18, 45, 58, 71, 72, 73). However, nematodes that are very deep in the soil may escape injury by fumigation (66). Although the plow-sole layer may limit gas penetration (65), many sandy fields do not have a plow sole. Fumigation is used extensively to control nematodes in greenhouses (30, 44, 46, 53), but living plants must be removed from the greenhouse before fumigation, as chloropicrin kills green vegetation (16, 19).

In the field, certain crops are so valuable that they justify fumigation of acres of land. Increased yields of several farm crops resulted from chloropicrin fumigation of soil in fields (23, 18, 34, 28, 29, 39, 43, 50). Thousands of acres of pineapple land were fumigated with chloropicrin in Hawaii, often by injections through mulch paper (33, 34). The fumigation of small spots in fields for setting widely spaced plants has been done in some cases, and this method has commercial possibilities (43). Spot treatments were adequate in controlling root knot in a field of watermelons in Georgia (63).

In addition to killing fungi and other pests, chloropicrin has been known to kill some of the nitrifying bacteria in the soil, but there was also some increase in ammonia nitrogen in the soil after fumigation (51, 54, 55). Chloropicrin fumigation is desirable because it results in partial sterilization of the soil and permits good growth of plants immediately after the gas has evaporated (51). Fumigation is therefore superior to ordinary heat sterilization of soil which kills all of the beneficial organisms and brings about changes in the soil that make it unfavorable for the growth of plants.

Besides killing root-knot nematodes, chloropicrin fumigation is also effective against the root-lesion or meadow nematode (21) and the bulb nematode (6, 7, 8). As a further aid in plant disease control, this fumigant often controlled species of fungi in many experiments (19, 70, 71, 72, 2, 13, 9, 12, 35, 36, 38, 42). Since weed control* is a main item of expense in farming it was of value to learn that chloropicrin killed most of the seeds, bulbs, and underground root-stocks of weeds (20, 71, 40, 69). In addition, chloropicrin also controlled insects and centipedes that damage certain plants (41, 42, 49).

Successful soil fumigation depends on proper conditions among which temperature and moisture are important. Soil temperatures continuously above 68° F., and soil moisture of 10 to 30 percent (depending on soil type, fumigant, and kind of pests present) are optimum conditions for control of soil organisms by chloropicrin (40, 51). Dosages have been

*Weed control by soil fumigation is discussed in the following book that arrived after this bulletin was completed: Robbins, W. W., A. S. Crafts, and R. N. Raynor. Weed Control. McGraw-Hill Book Co., New York. 1942.

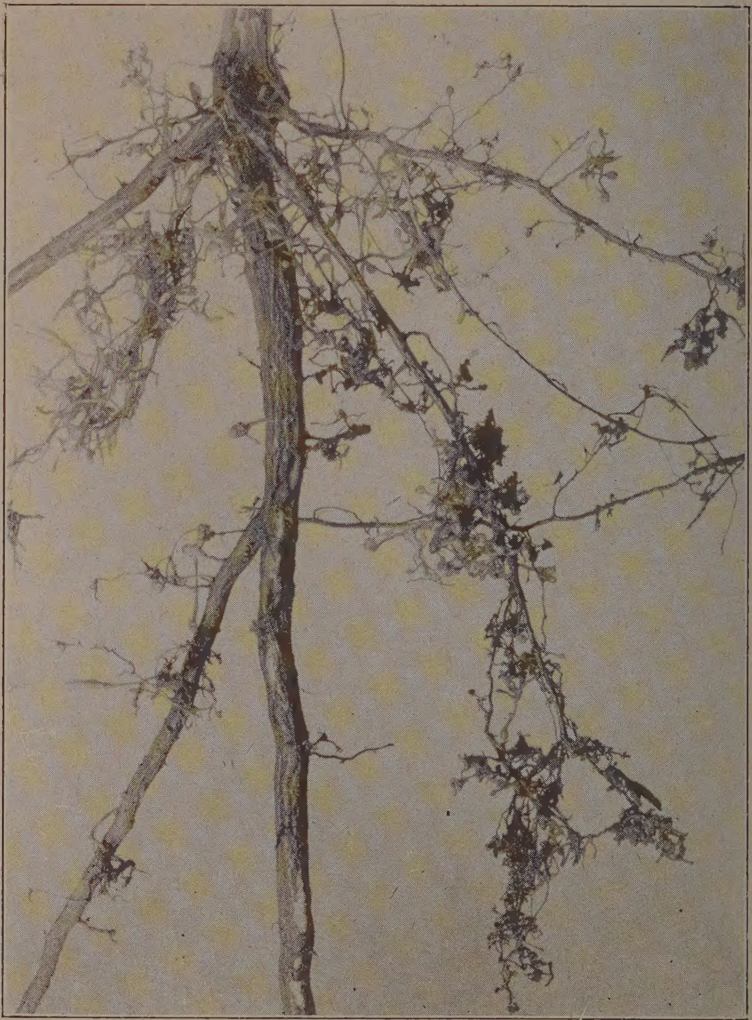

Figure 2. Rose roots with galls caused by the root-knot nematode. Small nematode galls such as these usually occur on woody plants (also on cotton).

calculated and spacing of injection holes determined for various conditions (72, 57, 6, 46, 61). The methods of soil fumigation are readily adapted for practical use in many places (24, 34, 19, 20, 72).

Figure 3. Boxwood plant (above) showing effects of root-lesion nematode, *Pratylenchus pratensis*. Note tufted condition of small rootlets. Below, separate rootlets from plant at top showing lesion type of injury and bunchy condition of the smaller roots caused by this nematode. (Specimen from Smith County, Texas, 1939.)

Sometimes fumigants are mixed before application. Root-knot and bulb nematodes were controlled by a mixture of chloropicrin with ethylene dichloride, while ethylene dichloride alone was sometimes ineffective (7, 8, 45, 58). In some tests, gasoline appeared to help chloropicrin in controlling nematodes (72). Soil fumigation with ethylene dichloride or paradichlorobenzene is the usual method of controlling peach tree borers in orchards in the eastern half of the United States (52, 14).

Carbon disulphide (locally called "highlife") is very useful as a fumigant for controlling root-knot nematodes in the soil, but it was ineffective against weeds, the Fusarium-wilt fungus, and damping-off fungi (24, 25, 60, 68, 58, 59, 70, 71, 72, 73). However this chemical controlled Armillaria root rot (64) and meadow nematodes (59, 60). Partial control of nematodes was obtained by evolving carbon disulphide gas from potassium xanthate (11).

In most tests, calcium cyanamid was unsatisfactory as a soil fumigant (31, 72, 56). However, a mixture of chloropicrin and cyanamid gave best results in killing fungi, nematodes, and weeds in tobacco seedbeds (5).

Hydrogen cyanide derived from calcium cyanide apparently was the first soil fumigant used in America to control pests in the soil (67, 4, 10, 42). The method of liberating this gas in the soil was improved by combining solutions of sodium cyanide and ammonium sulphate in the soil (68, 72). This method is in use for controlling nematodes in the field in Florida (68).

Methyl bromide is the most promising soil fumigant used in recent experiments in which it showed special advantages (22, 61, 62, 58, 26, 27, 49, 15). It is toxic in low concentrations, and penetrates the soil thoroughly because of its low boiling point, high vapor pressure, and low molecular weight. However, liquid methyl bromide boils at 40° F. so special equipment is necessary for handling this chemical. It is in commercial use (26).

When properly confined, formaldehyde controls soil pests satisfactorily and has been used extensively in greenhouses (25). However, it failed to control root-knot nematodes in the field (56, 72). Certain fungi were controlled by formaldehyde in carbon disulphide emulsion (25).

Tetrachlorethane and pentachlorethane controlled soil disease-producing organisms in some experiments, but these chemicals were slow to evaporate from the soil, due to their low vapor pressures and high molecular weights (1, 13, 74). However, tetrachlorethane was ineffective against root-knot nematodes according to one report (37). Dichloroethylether had some value as a nematocide (26), and orthodichlorobenzene killed alfalfa snout beetles (49).

EXPERIMENTS AT WESLACO

Fumigation of Soil in Gas-Tight Containers

In this series of tests, special methods were used as follows: The soil was Victoria fine sandy loam infested either naturally or artificially with root-knot nematodes, and was loose and fairly dry, containing usually about 8 to 10 percent moisture by weight on an air-dry basis. Containers were Cyanogas drums 22 inches high and 14 inches in diameter, containing 2 cubic feet of space. Unless otherwise specified, the chemicals were injected at two depths, equidistant from each other and from the top and bottom of the drum. This placement of the fumigant required diffusion of only 10 inches to reach all parts of the soil mass. After injection, the drums were sealed immediately with glue-coated Kraft duplex paper. Sealing was efficient in every case, as manifested by the strong odor of gas when the covers were removed, usually 4 days after treatment. The soil was ventilated for two or three days. Soil samples were placed in flower pots for the setting of indicator plants—usually tomato plants that had been started in sterilized soil. Data on the condition of the indicator-plant roots were taken after 30 days of growth, or later if temperatures were continuously low. In the tables (1, 2, 3, and 4), number ratings are given for degrees of nematode infestation, ranging from *1* (slight) to *6* (extremely heavy).

A test with chloropicrin, carbon disulphide and ethylene dichloride for root-knot control. This test was conducted in November, 1939. Starting with nematode-infested soil, supplementary inoculation was provided by mixing into the soil macerated infested tomato roots. Because the roots were not completely decayed, the efficiency of the fumigant treatment was decreased, which explains the poor results shown by chloropicrin in Table 1. Under the conditions of this test, with a large population of root-knot nematodes and eggs protected by undecayed roots, chloropicrin at 400 pounds per acre was not as efficient as carbon disulphide at 2000 pounds. The rate for ethlyene dichloride was high; but the fact that it was so efficient in nematode control was an important lead to further experimentation.

Effects of soil fumigants at different concentrations on root-knot and southern blight. The conditions for this experiment, conducted in May and June, 1940, were similar to those for the previous experiment, except that the temperature was considerably higher, and root materials in the soil were well decayed. Dry sclerotia of the southern blight fungus, *S. rolfsii*, inclosed in cheesecloth bags, were introduced into all of the cans. Results are shown in Table 2. Under the conditions of this test, the lethal dosage of ethylene dichloride for nematodes was between 1000 and 2000 pounds per acre, and for the dry sclerotia, more than 2000 pounds per acre. With carbon disulphide, 1000 pounds per acre killed all the nematodes but this treatment did not kill the fungous sclerotia, while 2000 pounds per acre killed both. With chloropicrin, 500 pounds per acre killed the nematodes, but one sclerotium of the fungus survived in one of the two treated drums.

Table 1. Effects of soil fumigation on root-knot nematodes and growth of tomato indicator plants in flower pots.

Chemical	Rate of Application		Fresh weight of stems and leaves—Oz.					Nematode Severity†				
	Ml. per cu. ft.	Lb. per acre ft.	Pot No. 1	2	3	4	Av.	Pot No. 1	2	3	4	Av.
None (check)	---	---	0.60	0.35	0.70	0.90	0.64	6	6	6	6	6.0
Chloropicrin	2.5	400	1.05	1.12	1.05	0.95	1.04	4	3	5	3	3.8
Chloropicrin*	2.5	400	0.75	0.80	1.35	1.05	0.99	4	3	5	2	3.5
Chloropicrin emulsion	2.5	400	0.75	1.05	0.70	1.10	0.90	3	3	4	4	3.5
Carbon disulphide	16.6	2000	1.05	0.60	1.25	0.85	0.94	0	0	0	0	0
Ethylene dichloride	50	6000	1.40	0.80	1.35	1.90	1.38	0	0	0	0	0
Vaporite‡	30	2722	0.75	0.85	1.30	0.40	0.82	6	4	6	1	4.2

*This chloropicrin treatment, at the same rate as the first, was at one point only, the center of the drum.
†Scale of severity from disease free (0) to extremely severe infection (6).
‡Vaporite is an English preparation used for the control of soil pests, including nematodes; it contains 15.75 percent naphthalene, and 16 percent creosote oils as active ingredients.

Table 2. Effects of various soil fumigants on southern-blight sclerotia and root-knot nematodes.

Chemical	Rate of application		Survival	
	Ml. per cu. ft.	Lbs. per A. ft.	S. rolfsii†	H. marioni‡
None (check)	—	—	5	5
Ethylene dichloride	8.23	1000	3	1.5
"	16.46	2000	2	0
"	32.92	4000	0	0
Carbon disulphide	8.29	1000	3	0
"	16.57	2000	0	0
Chloropicrin	3.17	500	0+tr.	0
"	6.35	1000	0	0

†Based on growth of sclerotia in plate cultures.
‡Root knot on indicator plants. Scale 0 to 5. Average of 5 plants.

Effects of soil fumigants on root-knot nematodes, nutgrass, and sclerotia of the fungi causing southern blight and cotton root rot. Two tests were conducted in the summer and fall of 1941, with methods similar to those previously described. As the boiling point of methyl bromide is very low, it was introduced into treatment drums in a low temperature room at the ice house in one case; in the other, it was poured quickly into cold soil from a bottle that had been kept in the freezing compartment of a refrigerator. This soil was then placed in the center of the drum, which was quickly filled and sealed. In the first test the nematode population was less than anticipated, and tomatoes as indicator plants in the non-treated soil gave readings of only 5, 8, 7, 95 and 15 galls respectively, in 5 separate pots. Sclerotia of *S. rolfsii* also appeared to have been killed throughout, except in the control drum.

The other test was conducted in October and November, 1941, using soil taken from a nematode-infested snapdragon bed. The soil was excessively moist when moved, and in drying to a point suitable for fumigation, the nematode population appears to have been greatly reduced. Sclerotia of the cotton root rot fungus, *Phymatotrichum omnivorum*, from flask cultures on sorghum seed and soil, and corms of nutgrass were introduced into all cans, in small paper bags. Also, some large nematode galls (⅝ inch in diameter) in paper bags were inserted into the drums treated with methyl bromide, with the highest rate of chloropicrin, and in the control.

Readings on survival of the fungus were taken by plate culture methods, after a period of ventilation to rid the material of absorbed fumigants. Readings on nematode survival were delayed for two months because of an extended period of cold weather that was obviously sufficient to retard nematode activity. Results are shown in Table 3.

For complete root-knot control, the necessary concentration of ethylene

Table 3. Effects of soil fumigation in sealed containers on cotton root rot sclerotia, nutgrass, root knot, and growth of tomato indicator plants. (Average of 5 plants in each case.)

Chemical	Rate of application		Survival			Height of plants after 60 days, inches
	Ml. per cu. ft.	Lbs. per A. ft.	P. omnivorum	Nutgrass	H. marioni	
None (check)	0	0	5	5	1.6	9.0
Ethylene dichloride	8.3	1000	5	3	tr.	11.2*
"	10	1200	0	0	tr.	10.6
"	11.6	1400	0	0	tr.	10.3
"	13.3	1600	0	0	0	11.7*
Chloropicrin	3.75	600	0	0	0	11.1*
"	5.0	800	0	0	0	11.8*
Methyl bromide	3.75	633	0	0	0	11.7*

*All significantly higher than the control plants.

dichloride in this experiment would appear to be between 1400 and 1600 pounds per acre foot. Both concentrations of chloropicrin and the methyl bromide completely killed the nutgrass, the nematodes and sclerotia of the cotton root rot fungus. The difference between readings 1 and 2 in nematode infestation amounted to 25 galls per pot. As the root systems of all plants were vigorous, penetrating the soil completely in 7-inch flower pots, even the readings of 2 appeared hardly detectable. It scarcely seems possible that so low an infestation could measurably affect the growth of the plants. For this reason, the fumigation apparently gave benefit in addition to nematode control.

The results from inoculation of soil with large galled roots that had been exposed to certain of the treatments are not shown in the table. The

Table 4. Effects of soil fumigation of a flower bed with chloropicrin and ethylene dichloride on nematode infestation of tomato indicator plants.

Chemical	Lb. per A. ft.*	Cover	Nematode survival
None (check)	0	None	5.0
Chloropicrin	500	Acid-proofed burlap bag material	1.4
"	500	Sisalkraft paper	0
Ethylene dichloride	1500	Bag material	2.6
"	1500	Sisalkraft paper	2.2

*An acre-foot designates the top foot of soil over an entire acre.

special gall material was removed, broken into small bits, and mixed into pots of sterilized soil for separate readings on survival. The methyl bromide treatment killed all stages of the nematodes, permitting the indicator plant to grow without a trace of root infestation; the strongest chloropicrin treatment showed a trace of infestation and the comparable nontreated root galls produced a heavy infestation. Methyl bromide showed great power of penetration, with lethal effects on nematode larvæ and eggs.

In a further test with methyl bromide, conducted in June, 1942, soils with 10, 12½, 15, 17½, and 20 percent moisture content on the air-dry basis were fumigated in drums of two cubic feet capacity at the rate of 2½ milliliters per cubic foot. The chemical was introduced into the previously sealed drums (Figure 8) by means of a special applicator whereby a measured amount is forced out by its own vapor pressure through a ¼-inch copper tube inserted through the paper. The tube was then removed and the hole quickly sealed. Various disease organisms had been introduced into the soil, in paper bags buried 4 inches deep and 12 inches in a direct line from the point of introduction of the gas. The introduced organisms were: moist pure-culture sclerotia of the cotton root rot fungus and of the southern blight fungus in cotton-stoppered test tubes; root-knot nematodes in old decayed root galls mixed with soil; root-knot nematodes in freshly collected tomato root galls ¾ inch in diameter; and ten recently dug nutgrass corms. After three days' exposure to the gas in the sealed drums, the organisms were removed and tested for viability. As tested by the usual methods (nutrient agar plates for the fungi, and indicator plants for the nematodes with readings at 30 days) the sclerotia of the fungi and all nematodes in both lots were killed in all the fumigated soils. The nutgrass corms were discolored internally, and failed to grow after planting in pots of soil. In contrast,

Figure 4. Marigolds (above) and stocks (below) growing in soils which were initially heavily infested with root-knot nematodes. Left, in each case, soil fumigated with chloropicrin at about 5 milliliters per cubic foot; right, nontreated soil. Note the improved growth of the plants in the fumigated soil.

all organisms in comparable nontreated lots of soil survived. This test constitutes further proof of the high penetrating power and high fungicidal and nematocidal value of methyl bromide, even in soils of relatively high moisture content, when the container is adequately sealed.

Fumigation of nematode-infested greenhouse soil. Figure 4 illustrates marigolds *(Tagetes sp.)* and stocks *(Mathiola incana)* about six weeks after planting in soil fumigated with chloropicrin, as compared with nontreated, nematode-infested soils. Striking differences in growth are evident, due to control of the root-knot disease.

Fumigation of outdoor plots

In these tests the chemical was injected 6 inches deep into the soil with a Vermorel Injector in measured dosages in holes 12 inches apart, followed by closing of the hole by pressure of the foot. As the operator proceeded along the plant bed, a gas-confining paper cover was placed over the bed in such a manner as to leave a 6-inch border on either side, extending down into a trench at the border (Figure 6). Soil was thrown onto the edge of the cover to hold it in place. After the bed was completely treated with the cover in place, with edges uniformly buried, the trench surrounding the bed was thoroughly wetted, thus making a wet-soil barrier against the escape of gas, extending both laterally and downward below the edge of the cover for several inches. The efficiency of such a barrier was repeatedly demonstrated by the strong odor of the chemicals when the covers were removed four days later.

Effects of chloropicrin fumigation of nematode-infested soil on subsequent growth of sweetpeas. Attention was called to failure of sweetpeas in a nursery in 1938-39, and examination disclosed heavy nematode infestation of all of the plants. In August, 1939, one of the beds was fumigated with chloropicrin at the rate of 4 milliliters per square foot of surface. A board frame surrounding the bed was sealed at the corners and at all junctions with adhesive tape. This was the base to which was glued a sheet of glue-coated, gas-impervious duplex Kraft paper. A 6-foot section in one end of the bed was left without treatment. The ground surrounding the treated bed was kept thoroughly moist. After a week of æration following the 4-day treatment period, sweetpeas were planted. The precaution of Rhizobium inoculation was taken because of the known lethal effects of chloropicrin on this nitrogen-fixing bacterium (23). The 24-foot section of the bed which was treated produced vigorous plants that attained a height of 7 feet, and bore flowers profusely from September to April. The nontreated end of the bed produced plants only 3 feet high, and these began to die early, with much less flower production for the season. Nematode infestation was heavy in the nontreated portion but lacking or very light in the treated end. This fumigation of the soil with chloropicrin gave practical control of root knot.

Control of the root-lesion nematode, Pratylenchus pratensis, in an eggplant seed bed and in a chrysanthemum bed. Following repeated failures to establish eggplants in a seed bed at Substation No. 19, Winter Haven, a

heavy infestation of the soil by the root-lesion nematode was found in May, 1937. Areas were fumigated with chloropicrin by standard methods, with adequate covers and wet borders. Plants set later in the treated beds grew rapidly from the start, in marked contrast to plantings in non-treated soil. This indicated this nematode was readily controlled by chloropicrin.

Chrysanthemums in a 30-foot bed at a commercial nursery near Weslaco had failed completely, with little or no commercial flower production. Examination disclosed the root-lesion nematode to be very abundant in the roots. Just prior to the 1939 planting, water was withheld from one plot, and it was deeply spaded twice to permit drying of the deeper layers. The soil was then fumigated with chloropicrin, using procedures as in the sweetpea experiment. On the second day after treatment, a heavy rain loosened the paper cover at several points. These were again sealed and the cover left on four days longer. After æration, 20 varieties of chrysanthemums from pots of sterilized soil were planted in rows across the 4-foot bed and the rows continued across a nearby bed of non-treated soil.

Thirty days after planting, the plants in the treated bed had an average height of 14.6 inches as compared with an average height of 10.4 inches

Figure 5. Chrysanthemums growing in soil that had been infested with the root-lesion nematode, *Pratylenchus pratensis*. Right: Soil fumigated with chloropicrin before planting. Left: nontreated soil. The plants in the left background were greatly dwarfed, and those in the left foreground largely killed by the infestation.

in the nontreated plot (Figure 5). Increase in height did not adequately depict the difference in growth, as all of the branches were likewise longer and the plants consequently wider in expanse of growth. Also, in all cases there were more branches and flowers on the plants in treated soil. More striking than the difference in growth was the difference in longevity of the plants, which was evident only 3 months after planting. At that time 96 percent of the plants were alive in the treated bed and only 20 percent were alive in the nontreated soil. Examination of the roots of sickly plants in the nontreated bed showed heavy infestation with the root-lesion nematode. There was very light infestation or none on plants in the treated bed.

Control of root-knot-nematode in snapdragons. In August, 1941, snapdragons died prematurely and failed to produce good flowers at a florist's nursery near Weslaco. Examination of the plants disclosed an extremely heavy infestation of root-knot nematodes. The bed was spaded twice in order to dry out excess moisture and then bedded with a 6-inch furrow on both sides. After three weeks, chloropicrin at 500 pounds per acre, and ethylene dichloride at 1500 pounds per acre, were injected into different portions, of the bed, and each portion separately was covered with covers of gas-impervious materials. At time of treatment the soil moisture at 8-inch depth was about 8.5 percent on an air dry basis. It was much wetter at lower depths. When the covers were removed four days after treatment, the odors of both gases were strong. After allowing several days for the gas to evaporate, pots of the treated soil were planted with tomato plants grown in nematode-free soil. At 30 days, readings on these plants were taken as shown in Table 4. In this test to show the relative efficiency of an acid-proof cloth bag material, as compared with Sisalkraft, the latter proved to be the better material for this purpose. Also, chloropicrin at 500 pounds per acre was definitely superior to ethylene dichloride at 1500 pounds in controlling root-knot nematodes under the conditions of this test. Sweet peas planted in September in the treated beds flowered profusely throughout the winter, indicating practical nematode control.

Fumigation of home flower beds with chloropicrin to eliminate nutgrass, Bermuda grass, and annual weeds. In a home flower garden at Weslaco, nutgrass *(Cyperus rotundus)*, Bermuda grass *(Capriola dactylon)*, and other weeds had become increasingly bad from year to year, requiring much hand labor to keep the beds in presentable condition. In October and November, 1941, several beds, approximately 4x30 feet, were fumigated with chloropicrin at the rate of 500 and 600 pounds per acre, using standard procedure. The covers used were 5-foot strips of Sisalkraft, a strong paper heavily reinforced with sisal fiber impregnated with asphalt-like material between two sheets of Kraft paper. At the end of eight weeks following treatment, the freedom of the treated beds from troublesome weeds was strikingly evident. Only occasional nutgrass plants developed and these always came from deep corms. In the upper layers of soil many dead corms were found. Bermuda grass, likewise, was almost

Table 5. Effect of chloropicrin fumigation on prevalence of weeds in two separate flower beds.

Chemical	Lb. per A. ft.	Numbers of plants per sq. yd.		Annual weeds (Av. of 5 plots)
		Nut-grass	Bermuda grass	
Two months after treatment No. 1				
None (check)	0	14.2	25.2	98.2
Chloropicrin	600	1.8	0.6	2.4
Four months after treatment No. 2				
None (check)	0	0*	30.0	91
Chloropicrin	500	0	1.0	6.2

*This bed contained no nutgrass plants.

completely eradicated. Counts of weeds in comparable treated and non-treated areas are given in Table 5. In one case the paper cover, upon removal, was dragged onto the lawn where it laid over night and the next day. Much top burning of the grass resulted. The release of the chloropicrin from the asphalt material in the paper in which the gas had been absorbed was sufficient to cause the injury. After the first mowing, the injury was no longer evident.

The cost of chemical used for 120 square feet of bed, at the retail price for small quantities, was $1.60 to $1.80, depending upon rate of application; the cost of the cover, which was used repeatedly in different plots, was $1.50; the time required for treatment was less than an hour for one man. The few remaining weeds were readily removed. An appreciable saving in hours of labor compared with that required by hand weeding through the season was indicated. Furthermore, the injury to growing plants brought about by repeated weedings was eliminated. For weed control alone, plant-bed fumigation apparently was justified in this case. In addition, however, superior plant growth resulted even though the presence of nematodes or other plant pests in the ground may not have been recognized. During the preceding year, it had been difficult to control nutgrass, Bermuda grass, and annual weeds in this bed.

Four of the above beds had been planted the year before (1941, a wet season) with Dutch bulbous iris, and when the bulbs were dug in June, a loss of approximately 50 percent from southern blight *(S. rolfsii)* had occurred. The same beds, fumigated with chloropicrin at 500 pounds per acre by standard methods were planted to Wedgewood iris in November and December, 1941. When dug in May, 1942, only 5 out of 780 plants showed *S. rolfsii* infection, and these were all growing at the margins of the beds where the soil had been wetted for gas confinement at the time of fumigation. In a comparable non-fumigated bed, 42 out of 127 iris plants (33 percent) were killed by southern blight. In this test, satisfactory control of the disease in out-door beds was obtained by chloropicrin fumigation.

EXPERIMENTS AT JACKSONVILLE

Fumigation of Field Plots

These experiments were conducted on Norfolk fine sand and Ruston fine sandy loam soils in a single field in which most of the tomato plants had wilt, caused by the fungus, *Fusarium lycopersici* Sacc., and root knot. The soil in the experimental plots (40, 50, or 80 square feet) was loosened to a depth of 10 inches in preparation for fumigation. Most of the large roots and lumps of soil were removed from these plots and the chemicals were injected at an 8-inch depth. Seed were planted in the soil one or two weeks after treatment and the test plants were dug and examined 2 to 3½ months after soil fumigation. Table 6 gives the standard conditions covering the results presented in Tables 7 to 9.

The soil was dry or slightly moist at the time of fumigation with a moisture content ranging from 2.8 to 4.4 (air dry basis) in Series 9, 11, and 13. Fumigation was started in soil that was 65° F. or warmer. However, colder weather occurred within the 5-day period of fumigation in Series 5, 9 and 13, which helped some organisms to survive the fumigation. In Series 5, the soil was too cool and moist during fumigation, and a total of 6.56 inches of precipitation from four rains within two weeks probably washed soil from unsterilized land into the treated plots. Results from Series 5 are included to show the degree of root-knot control when conditions were unfavorable (Table 9).

Table 6. Standard data on series of soil treatments at Jacksonville.

Series No.	Date of treatment	Soil T., deg. F.	Plot border	Soil cover	Sealing of covers	Applicators
1	8-6-36	90 to 100	Boards	Glue-coated paper	Banked	Tube-peg board*
2	9-9-36	85 to 95	"	" "	"	" "
3	4-19-37	70 to 80	"	" " wet soil	"	Carbona Prod*
4	7-26-37	90 to 100	"	Glue-tar paper " "	"	" "
5	3-14-38	55 to 83	"	Duplex glue paper, " "	"	" "
6	8-22-38	83 to 101	"	" " " " "	"	" "
7	3-20-39	68 to 80	"	" " " " "	"	Vermorel Pal†
8	3-22-39	66 to 80	"	" " " " "	"	" "
9	3-28-40	58 to 83	Sheet metal	" " " " "	Nailed	" "
10	5-11-40	65 to 86	Ditch	Special cloth	"	" "
11	8-26-40	72 to 90	Sheet metal	Duplex-glue paper	"	Isco Larvajector†
12	7-26-41	88 to 103	" "	" "	"	Larvajector R.
13	3-24-42	48 to 68	" "	" "	"	" "
14	4-6-42	50 to 70	Ditch	Wet soil, only	----	Mack's Antiweed Gun

*For applications with the tube-peg board and Carbona Prod, the mixture of 15 percent chloropicrin with 85 percent white gasoline was used

†For the Vermorel Pal and the first model of the Larvajector, the fumigants were mixed with 4 percent refined cottonseed oil for lubrication of the applicaator.

Sheet metal borders, 36 inches wide were set 30 inches deep in the soil to prevent the entrance of gophers, moles, worms, and nematodes from the outside through the soil or along the roots of the test plants. The tops of the metal sheets were nailed to wooden borders. Immediately after fumigation, most of the plots were covered with glue-coated paper

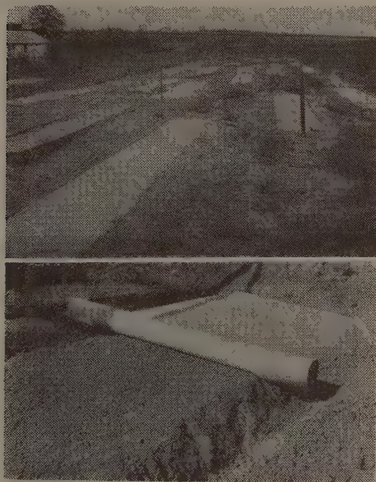

Figure 6. Above, soil plots that were fumigated with chloropicrin and carbon bisulphide, and immediately covered with glue-coated paper. Photographed at Jacksonville, March 18, 1938. Below: a single plot at Weslaco prepared for fumigation. A roll of gas-impervious paper has been placed in position and the furrow around the plot is deep enough for covering the edges of the paper.

to delay the escape of the fumigants. Because of the cost of this paper, the cheaper, wet soil (water seal) method was tested for comparison and used as follows: The top half inch of the soil was wetted before the fumigants were injected, and then the soil was soaked to depths of two or three inches for about three days. This confined chloropicrin and carbon disulphide fairly well, as both are insoluble in water.

Only rough lumber was used in the experiments at Jacksonville, so it was impractical to seal the edges of the cover papers onto the boards with glue. In some cases, wood strips were nailed over the edges of the paper; in other cases, the paper was extended over the boards and the edges were banked with moist soil. In no case was it practical to use the almost perfect seal as recommended in our description of most desirable methods. Imperfect sealing of the edges of the paper cover permitted leaking of fumigants which decreased their concentrations and efficiency. The tables show the concentrations of chemicals necessary for good results under these conditions. Paper covers were left on the soil for five days to delay the escape of the fumigants. Thereafter, the covers were removed and the soil was stirred to accelerate the evaporation of the fumigants from the soil. The odors of the fumigants usually were notice-

able at this time. Other information on materials and methods for soil fumigation has been published previously, (Young, 72).

In these treatments, the following volatile liquids (which change to gases after injection) were tested: chloropicrin, carbon disulphide, ethylene dichloride, pentachlorethane, tetrachlorethane, and xylene. Other chemicals tested were: formaldehyde (37 percent solution) applied at the rate of 1000 pounds per acre; sodium hydroxide (2 percent solution) was sprinkled on the soil; powdered Aero Cyanamid was thoroughly mixed with the upper 10 inches of soil (in amounts that made it unfavorable for plant growth); and a powder named IN2391-A2 from E. I. du Pont de Nemours Co., was mixed thoroughly with the upper 6 inches of soil and the soil was abundantly irrigated. In a few tests, hydrocyanic acid was generated in the soil by applying a solution of sodium cyanide, watering the soil abundantly, then watering the soil with a solution of ammonium sulphate, and finally soaking the soil with water (68).

Dixie Queen watermelon, Greenpod okra, and Whippoorwill cowpeas were used as indicator plants to test the effectiveness of fumigation in controlling nematodes. The roots of the test plants were dug and washed for examination. Percentages of plants with severe root knot, as shown in Tables 7, 8, and 9, indicate the serious damage from root

Table 7. Effects of soil fumigation with different concentrations of chloropicrin and carbon disulphide on watermelon root knot and weeds. Series 3.

Chemical	Pounds per acre	Kind of cover	Number of				Percentage of plants with root knot	
			Plots	Water-melon plants	Johnson grass stems	Other weeds	Total	Severe
None (check)	0	Air	10	437	655	2128	72.5	35.5
Chloropicrin	400	Glue-paper	2	83	2	92	0	0
"	300	"	4	238	2	230	3.4	0.8
"	200	"	2	113	0	106	12.4	0.9
"	100	"	1	61	72	18	52.5	27.9
Carbon disulphide	2000	"	1	86	3	236	1.2	0
"	2000	Water	2	108	17	2200*	0.9	0
"	1500	Glue-paper	3	159	2	1587	0.6	0
"	1500	Water	2	98	17	2200*	2.2	0
"	1000	Glue-paper	3	155	33	1398	1.3	0
"	1000	Water	2	104	12	2200*	0	0
"	500	Glue-paper	3	175	12	1783	77.7	42.9

*Estimated.

knot and the efficiency of the control methods. Root knot was classified as *severe* when the roots showed many knots, or knots ¼ to 1 inch in diameter. The disease was classified as a *trace* when a plant showed only one or a few knots 1/32 to ⅛ inch in diameter.

Control of root knot with chloropicrin. Soil fumigation with chloropicrin at rates of 300 to 600 pounds per acre, with effective covers, usually controlled root knot satisfactorily, as indicated by the small amount of severe root knot on the test plants in treated plots. These results are given in Tables 7 and 8, which contain data only from plots in which

conditions favored effective fumigation. Table 9 includes tests in which certain conditions were unfavorable to the best action of some chemicals. The different concentrations were grouped in this table on the basis of similar effectiveness. The nematodes were perfectly controlled in many of the test plots. Applications of 100 to 200 pounds of chloropicrin per acre usually did not give good control. The gasoline-chloropicrin mixture contained nearly six times as much gasoline as chloropicrin in Series 1 to 6, and by using 300 pounds of chloropicrin per acre, the treatment also included 1700 pounds per acre of gasoline. Root knot was well controlled in many plots fumigated with this mixture, but the low concentration of chloropicrin generally was less effective in later plots in which the chloropicrin was used alone. This indicated that the gasoline aided the chloropicrin in killing root-knot nematodes. In the later series, concentrations of 400 to 600 pounds of chloropicrin per acre were necessary for best results (Table 8). Soil with old nondecomposed roots or cold damp soil were unfavorable for efficient fumigation with chloropicrin (Table 9). Root knot was extremely severe in the comparable untreated plots in all of these tests.

Control of root knot with carbon disulphide. Fumigation of soil with 1000 to 3000 pounds of carbon disulphide per acre controlled all or nearly all of the root-knot nematodes in plots with satisfactory covers (Tables 7, 8, and 9) while 500 to 800 pounds of carbon disulphide per acre usually failed to give satisfactory control. Carbon disulphide was ineffective against weeds (Table 7).

Table 8. Effects of different chemicals and varying concentrations in controlling root knot. Period of years' summary.

Chemicals	Pounds per acre	Series No.	Number of		Percent of plants		
			Plots	Plants	Without root knot	With root knot	
						Trace	Severe
None	0	All	136	11888	0	20	80
Chloropicrin	100–150	2,3	2	131	62	18	20
"	200–250	3,4,7,8	11	1845	84	12	4
"	300–320	2,3,6 9	37	6623	31	68	3
"	350–750	1,4,6–11	38	7329	96	3	1
Carbon disulphide	500	3	3	175	22	35	43
"	750	4	2	130	92	8	0
"	1000–2250	1,3,4,6	15	1203	98	2	0
"	750–2000	3,4,6	14	1130	97	3	0
Ethylene dichloride	1500	11	4	1004	22	31	47
Sodium cyanide	800	4	3	167	89	8	3
"	1200	4	3	108	71	26	3
Cyanamid	1000	4	1	69	45	36	19
"	1500	4	1	11	46	54	0
Formaldehyde	1000	6	5	724	33	44	23
Sodium hydroxide	1470	5	2	172	0	13	87
DuPont IN2391-A2	500	13	1	115	91	6	3

Control of root knot with other chemicals. Tetrachlorethane, pentachlorethane, and xylene at concentrations of 1000 and 2000 pounds per acre controlled the nematodes satisfactorily in most cases. Xylene evaporated from the soil so promptly that seed would germinate in the soil only five days after it was ventilated and planted, but tetrachlorethane remained toxic and noticeable in the soil for 10 days or longer, and pentachlorethane was toxic 18 days after the covers were removed. The slow evaporation of these latter chemicals is correlated with their low vapor pressures (Table 12) and seed planted too soon in soil treated with these materials were killed. Hydrocyanic acid gas released from sodium cyanide by ammonium sulphate reduced severe root knot to 3 percent of the plants, but left the soil very hard with black and white patches. This treatment added a ton of soluble salts per acre to the soil, and even after several inches of rain with supplementary irrigation, the toxic chemicals were not sufficiently removed to permit good growth of plants. Cyanamid failed to control root knot, and prevented good growth of watermelons. Sodium hydroxide (soda lye) apparently did not decrease the abundance of the nematodes in the soil. Although in laboratory tests by other workers, ethylene dichloride and formaldehyde controlled soil parasites, neither of these chemicals controlled nematodes satisfactorily in the field plots at Jacksonville. DuPont IN2391-A2 in a metal-bordered plot gave good control of root knot (Table 8), but was unsatisfactory in the plots with board or ditch borders (Table 9).

Confining fumigants in the soil. Different kinds of covers were tested for confining chloropicrin and carbon disulphide in the soil. No important difference in thoroughness of disinfection of field plots were found to be due to differences between hoof-and-horn glue, casein glue, or vegetable paste on the cover papers, so the summary data were calculated together for the different groups of plots covered with these materials. Papers with these three kinds of gas-proofing materials were most satisfactory in aiding the fumigants to control root knot. Asphalt-covered paper gave fairly good results. In Series 10, a special cloth cover was only partly impervious to chloropicrin and with this cover the chemicals controlled only 86 percent of the root knot.

Tests were conducted to determine whether the water seal (wet-soil cover) would effectively confine gases in the soil for root-knot control. The wet-soil seal gave good results in most of the test plots. This previously published conclusion was confirmed in Series 9. The wet-soil seal is practical for soil fumigation where the expense is to be minimized and perfect control of root knot is not required. As the comparable tests with glue-coated paper covers gave results only a little better than the wet-soil seal, data from both kinds of covers were calculated together in Tables 7 to 9.

Odors of fumigated soils. Most plots fumigated with chloropicrin, tetrachlorethane, and pentachlorethane emitted strong oders of these chemicals when they were uncovered within four days after fumigation was started. Soil fumigated with either chloropicrin or carbon disulphide

Table 9. Control of root-knot nematodes by soil fumigation under unfavorable conditions.

Chemical	Pounds per acre	Special conditions during and following treatment	Series No.	Number of Plots	Number of Plants	Percentage of plants with root knot: Trace	Percentage of plants with root knot: Severe
None	0	Cold soil, followed by rain	5	25	1978	14	74
Chloropicrin	300	"	5	9	1135	25	20
Carbon disulphide	3000	"	5	3	387	8	1
"	1000	"	5	9	1318	34	14
None	0	Soil with undecayed root knots	12	10	864	4	91
Pentachlorethane	2000	"	12	3	495	1	0
Tetrachlorethane	2000	"	12	3	533	3	1
Xylene	2000	"	12	2	156	7	3
Chloropicrin	480	"	12	2	288	12	47
None	0	Rain 2 days after treatment	13	11	554	3	94
Chloropicrin	480	"	13	2	453	0.2	1
Tetrachlorethane	1000	"	13	2	222	1	0
Pentachlorethane	1000	"	13	2	164	21	0
Xylene	1000	"	13	2	111	2	1
DuPont IN2391-A2	500	Wooden border	13	1	89	7	9
None	0	Ditch borders; heavy rains	14	3	196	2	97
Carbon disulphide	1000	"	14	4	398	13	14
DuPont IN2391-A2	500	"	14	2	207	23	69

retained a characteristic odor unlike these chemicals or unfumigated soil, after the true odor of the chemicals was no longer present.

Spacing of injection holes. In Series 1 to 6, injection holes were 15 inches apart, and were 12 inches apart in Series 8 to 14. Chloropicrin was injected into holes 12 inches apart for comparison with injection holes 15 inches apart in Series 7. (Table 6.) There was no apparent difference in effectiveness of the chemical due to this difference in the spacing of the injection holes. The 10-inch spacing recommended in other states is not necessary in the sandy soil of East Texas.

Weed control. With glue coated paper covers, chloropicrin at rates of 300 to 600 pounds per acre usually controlled most of the weeds, especially Johnson grass, crab grass, and species of Cenchrus and Amaranthus, as was shown mainly in Series 3 and 5 (Table 7). At the rate of 100 pounds per acre, chloropicrin did not control weeds, and none of the concentrations of carbon disulphide controlled weeds. Because dry weed seeds are resistant to chemicals, poor weed control was obtained by fumigating dry soil. The wet-soil seal was ineffective in facilitating weed control.

Fumigation of plant beds. Using glue-coated paper covers, seven hot beds and fourteen cold frames were fumigated with chloropicrin at rates of 400 to 600 pounds per acre each year from 1937 to 1942, with satisfactory control of tomato diseases. The greenhouse ground bed at Substation No. 11 was fumigated with chloropicrin at 400 pounds per acre in 1939 and 1940, and with carbon disulphide in 1942 with satisfactory results.

Control of damping-off parasites

Many experiments were conducted from 1936 to 1942 on the control of damping-off of tomato and cabbage seedlings by soil fumigation and seed treatment. Fertile soil abundantly infested with damping-off fungi, especially species of Pythium and Rhizoctonia, were used in these tests each year. Metal trays each holding 25 pounds of this soil were used as containers. Conditions favoring post-emergence damping-off prevailed in the experiments in 1937 and 1938, as the trays were kept in the laboratory building where the seedlings received insufficient light (50-300 foot candles) which resulted in spindly seedlings. In 1939, the trays were kept in an out-door hot bed with adequate light and ventilation. Tomato seed for every tray (except those treated with formaldehyde) was dusted with red Cuprocide at the rate of 2½ percent (by weight of seed) before planting.

The different treatments were: (1) Dry soil in an iron barrel with glue-coated paper cover was fumigated with 10 milliliters of chloropicrin per cubic foot of soil for 4 days. An excess of fumigant was used because the cover could not be glued to the top of the barrel. (2) Dry soil was also fumigated with 1 milliliter of carbon disulphide per pound of soil in the iron barrel covered with glue-coated paper. (3) Moist soil was mixed with 100 milliliters of 6 percent formaldehyde solution per tray, seeds were planted in the tray 1 day later, and the soil was watered abuntantly. (4) Semesan suspension (0.25 percent) was sprinkled at the rate of 142 milliliters per square foot on the soil immediately after the seed was planted, and this treatment was repeated seven days later. (5) Red Cuprocide suspension (0.25 percent) at the rate of 568 milliliters per square foot was sprinkled on the soil immediately after the seed was planted, and this treatment was repeated seven days later.

The population of seedlings changed from day to day, being increased by delayed germination of seed, and decreased by post-emergence damping-off, after an initial stand of seedlings was obtained. The seedlings were counted every seven to ten days. As used here, the term "emerged" means the largest number of seedlings found in a given tray at any count. The "percentage of emerged seedlings" was based on the number of seeds planted per tray, and the control of pre-emergence damping-off was summarized from these data. A different basis was necessary for calculating percentages of seedlings with post-emergence damping-off, as the counts came from emerged seedlings that were visibly damped-off. Hence, the total number of seedlings with post-emergence damping-off divided by the largest number of seedlings found in the tray at any one time gave the percentage of seedlings with post-emergence damping-off. Because of the different basis of calculation, there was no relation between the percentages with pre-emergence and post-emergence damping-off.

Data on the damping-off experiments are summarized in Table 10, in which each percentage is an average of the data from 2 to 4 trays each planted with 500 tomato seeds. Chloropicrin was the most effective of

Table 10. Chemical treatment of soil to control damping-off of tomato seedlings.

Chemical	Percentage of seedlings emerged			Percentage of seedlings lost by post-emergence damping-off		
	1937	1938	1939	1937	1938	1939
None	19	36	25	40	73	1
Chloropicrin	49	70	64	2	18	0
Carbon disulphide	--	51	--	--	50	--
Semesan	32	58	54	4	25	1
Cuprocide	32	62	--	2	10	--
Formaldehyde	--	73	31	--	20	0

the chemicals used in the soil to control damping-off of seedlings. Carbon disulphide was unsatisfactory for this purpose. Formaldehyde gave excellent results in 1938, but killed most of the seeds in 1939. Thus, formaldehyde was erratic and sometimes very injurious in its effects. Semesan and Cuprocide were both valuable in decreasing post-emergence damping-off of seedlings.

Fumigation box. At Jacksonville, soil for pots, flats and greenhouse benches was conveniently fumigated in a gas-tight box 3x3x3 feet built of center-match lumber glued together and well painted. The soil was fumigated on January 27, 1942 at the rate of 7 milliliters per cubic foot. The Larvajector was used to inject the chloropicrin into holes one foot apart horizontally, at the 6, 18, and 30-inch vertical levels. The tightly fitting lid was placed on the box and sealed onto the sides of the box with glue-coated paper sold as French tape. Due to the cold weather, 60 feet of electric heating cable was arranged in the central part of the soil in the box and maintained the soil at 76° to 102° F. during fumigation. After a week of fumigation, the soil was ventilated and transferred to the laboratory hot bed that had been disinfected with creosote. The tomatoes grew well in the fumigated soil, and they were healthy when transplanted into a cold frame in March.

FACTORS INFLUENCING THE EFFECTIVENESS OF SOIL FUMIGATION

Soil type. A loose permeable soil such as sandy loam is most easily fumigated and is most likely to show good results from fumigation. Heavy clay soils are apt to show erratic results unless soil preparation has been such as to leave the soil in a uniformly loose condition to the depth to which sterilization is desired. A plow-sole may limit penetration of fumigating gases, so that organisms below that layer may remain alive and cause infections in subsequent crop plants. In any type of soil, fumigating should give effective results if moisture, temperature and tilth are correct and if gas confinement is efficient.

Soil moisture. Fumigants insoluble in water cannot effectively penetrate wet soil. Also, these fumigants often fail to kill large weed seeds and the sclerotia of certain fungi in powdery, dry soil because seeds and sclerotia are resistant when very dry. For best fumigation, therefore, sandy loam soil should have sufficient moisture to partially hold its shape when a sample of it is squeezed in the hand. Usually, a moisture content of 5 to 15 percent on the air-dry basis is satisfactory Heavy clay soil should be nearly dry, as its colloidal properties make it nearly impervious to gases when more than slightly wet. Effective pest control in layers of wet soil cannot be obtained with fumigants that are insoluble in water.

Soil temperature. For best results with chloropicrin, the temperature of the soil at a depth of six inches should be warmer than 65° F. Rapidity of penetration and killing increase with rises in temperature. Potting soils can be fumigated in warm weather and stored for winter use. Most of the fumigants are inefficient below 45° F. Carbon disulphide, because of its much higher vapor pressure, penetrates better than chloropicrin at the lower temperatures. Methyl bromide has the lowest boiling point of all the fumigants tested and therefore gives uniformly good results at lower temperature. At 50° F. it is effective in killing insects, and probably would be lethal to nematodes and fungi also.

Soil preparation. Any fertilizers and conditioners such as sand, peat, or manure should be added to the soil before fumigation, and the soil should be loosened by plowing or spading to the depth to which effective pest con-

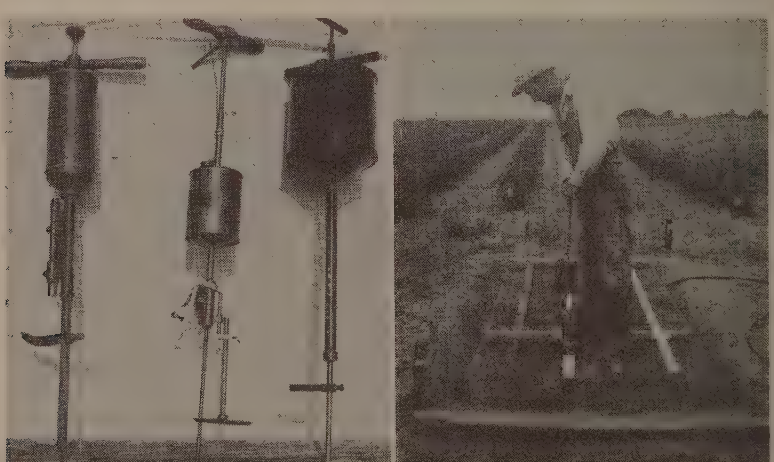

Figure 7. At left, three kinds of injectors of soil fumigants. Vermorel Pal injector (left); Isco Larvajector, (center); and Mack Anti-Weed Gun (right). At right, the Isco Larvajector in use. Immediately after the chemical is injected the soil is covered with glue-coated paper the edges of which are covered with soil and wetted down.

trol is desired. Large lumps should be broken or removed. Following the removal of the previous crop at least two weeks should elapse before fumigation to permit sufficient decay of roots infested with parasites. Effective nematode control usually cannot be obtained if undecayed roots of a previously infested crop remain in the soil.

Injection of chemicals. For potting soils in drums, barrels, or tight boxes, or for small plots of ground, the chemicals can be poured directly into holes, which should be immediately closed. A small commercial applicator called "Larvajector Jr."[1] screwed onto a bottle, makes a convenient apparatus for injecting measured dosages into small volumes of soil. Large applicators can be purchased that are convenient for large scale applications. The Larvajector[1], Vermorel Pal[2], the Carbona Prod[3], Mack's Anti-Weed Gun[3], (Figure 7) are designed to insert measured dosages as deeply into the soil as required, leaving only a small opening on the surface, which can quickly be closed by a thrust of the foot. These applicators are suitable for chloropicrin, carbon disulphide, tetrachlorethane, pentachlorethane, xylene, and ethlyene dichloride. Methyl bromide, with a boiling point about 40° F., requires special injection methods

Figure 8. A Dow Chemical Company methyl-bromide-applicator in operation. The methyl bromide liquid is forced by its own pressure from the original container into a closed, calibrated cylinder in quantities as desired. By opening the second tap, the liquid is forced through a copper tube into the soil at any desired depth.

(Figure 8). Injection of this chemical as a gas directly under a gas-impervious cover is an efficient means of application. In some experiments, cold methyl bromide from a container kept in a refrigerator was applied first to nearly frozen soil in a small container and then quickly

[1]Sold by: Innis Speiden Company, 117 Liberty St., New York; Southern Construction and Mill Supply Company, Houston, Texas.
[2]Sold by P. E. Lirio, Vineland, N. J.
[3]Sold by Wheeler, Reynolds, and Stauffer, San Francisco, California.

transferred to the large container of soil which was immediately sealed. This method gave excellent results.

Rates of application. In soils heavily infested with nematodes, weeds, or disease-producing fungi or bacteria, effective treatment cannot be expected with less than 400 pounds of chloropicrin or 1000 pounds of carbon disulphide unless gas confinement is unusually tight, and other factors are nearly optimum. Dosages at least 50 percent larger than these rates should be applied when: (1) it is impracticable to seal the gases completely in the soil during the period of exposure; (2) the temperature is below 65° F. at the time of treatment; (3) the moisture content of the soil is above the optimum; (4) the soil is of a heavy clay type; and (5) highest efficiency in pest control is of greater importance than economy of materials. With methyl bromide, the same general principles govern rates of application. However, preliminary results that have been reported indicate that this chemical is effective at smaller dosages than the other chemicals. One milliliter of methyl bromide per cubic foot of soil, equivalent to 166 pounds per acre foot, is very effective.

Methods of gas confinement. Two methods of gas confinement have been found to be practicable; a gas-impervious cover and a water barrier. For most thorough pest control, the surface of the soil should be promptly and completely covered with glue-coated paper or some other gas-impervious material. This must be adequately sealed at the edges and ends of the treated plot, either by sealing it to a previously prepared board border or by burying the edges of the paper to a depth of 5 inches and saturating the soil around the entire border with water. Several paper companies[1] manufacture either a glue-coated single sheet or a duplex Kraft paper with glue as an adhesive for holding the two sheets together. Both are efficient for gas confinement, but neither will withstand repeated use. A water-resisting paper of the Kraft duplex type, suitable for repeated use, would be highly desirable. Another material, in common use for other purposes in greenhouses is Sisalkraft[2], a very strong duplex paper fortified by sisal fibers impregnated with an asphalt compound. It is not completely desirable because of the absorption of chloropicrin by the asphalt. However, its strength and water resisting properties, and the fact that it can be used repeatedly, make it useful for confining the gases. Practical tests in field plots have shown that this paper confines the gas adequately for four days. Other materials that have been used are rubberized materials (not sufficiently impervious to chloropicrin) and cellophane covered fabrics or cellulose acetate impregnated materials, which are not sufficiently durable. An objection to the commercial use of the gas impervious cover is its cost and the expense of application. It is to be recommended primarily for seed and nursery beds and for special nursery and home gardens in which practically complete control of pests is highly desirable.

[1]The Western Waxed Paper Co., North Portland, Oregon; Chase Bag Co., 1111 Lamar St., S. Dallas, Texas; Arkell Safety Bag Co., 10 E. 40th St., New York, N. Y.

[2]The Sisalkraft Co., 205 W. Wacker Drive, Chicago, Ill.

With the water-seal method, the top half-inch of soil is wetted before fumigation, the fumigant is injected, and the soil then is soaked to a depth of one inch and kept wet for the entire period of fumigation. A modification of this is to cover the soil with newspaper, burlap, peat moss, or manure, which is kept thoroughly wet during the period of fumigation. A weakness of the method is the danger of permitting the covering layer to become dry on a sunny day or during a period of low humidity before the fumigation is complete. Because the gases quickly escape from the soil through such materials when dry, thus lowering the efficiency of fumigation, repeated sprinklings are required. Another objection is that nematodes, weed seeds, and other pests within the layer of wet soil are protected from the fumigating gas. However, the water seal (wet soil) method has been found to give 95 percent or better control of nematodes, which is adequate for most annual crops. It is not satisfactory for weed control. The method is less costly than one requiring an expensive covering material.

A reliable criterion as to the effectiveness of gas-confining measures is the presence or absence of the characteristic odor of the gas in the soil at the close of the fumigation period. Effective pest control can be obtained only if, within two days after application, the odor of the gas is strongly present in the soil. If the odor is still present at the end of four days, very good results may be expected.

Gas elimination. Gas-confining covers should be removed after four or more days. If the wet-top-soil method has been used, drying of this layer can be hastened by cultivation. With most of the fumigants, complete elimination of the gas can be expected in two to four days, provided correct conditions of moisture and temperature were maintained at time of application and later. Soils that were too wet, too cool, or sticky when treated, or that were wet by rains following the treatment, require one of three weeks be fore planting. Sometimes reworking the soil may be necessary. It is not safe to plant seed or set plants in fumigated soils when the characteristic odor of the gas used can still be detected in a handful of soil taken from a depth of eight inches.

Effects of fumigation on the soil. Chloropicrin, carbon disulphide, ethylene dichloride, xylene, and methyl bromide all evaporate almost completely, and leave no toxic residues in the soil. They do not change the physical structure of the soil. Plants grow well in soils fumigated with these chemicals probably because of the reduction or elimination of plant pests.

Prevention of recontamination. Care should be taken to prevent recontamination of fumigated soils. Recontamination commonly occurs by (1) direct mixing of nontreated soil with the treated soil; (2) use of contaminated tools that were used recently in infested soils; (3) movement of parasites in soil by water flowing from infested areas onto the treated plots; (4) invasion by organisms from nontreated adjacent areas; (5) storage of treated soil in contaminated containers and (6) movement of gophers and moles through the soil from infested areas.

Pots, flats, and tools can be fumigated readily in a fumigation box or bin, or they can be dipped in any strong disinfectant such as 5 percent formaldehyde solution before being used with fumigated soil. Greenhouse benches can be cleaned and disinfected by forcing live steam into all cracks and corners, by hot water, or by any strong disinfectant. Only plants from treated soils should be set in the fumigated soil. Border contamination can be avoided by inserting a barrier, even a strip of tar paper, vertically into a trench 2 or 3 feet deep around the edges of the treated soil. Soil fumigation may be effective through several plantings until the soil becomes recontaminated, or until a residue of infestation increases to injurious proportions.

COST OF SOIL FUMIGATION

All treatments that control soil-borne plant pests are expensive. However, the costs of soil fumigation compare favorably with those of other methods that are equally effective. In choosing a method, factors besides cost should be considered. Effects on the soil and date of safe planting following treatment are important. If the fumigation method is selected, the choice of the fumigant should be based on the nature of the predominating pest to be combated as well as on the cost of material. If only one type of organism is to be fought, the cheapest available material that is effective will probably be selected. If more than one organism is to be controlled, then a fumigant that will be general in effectiveness would be desirable. Other factors to be considered are: ready availability of the fumigant and applicators, ease of application without danger to the operator, amount of risk involved such as the explosion hazard and danger to nearby growing plants.

Table 11. Comparison of fumigants as to effectiveness and the relative cost of treatment.

Chemical	Lb. per 1000 sq. ft.	Effectiveness against				Cost	
		Nematodes	Fungi	Insects	Weeds	Per. lb. bulk	Per 1000 sq. ft.
Chloropicrin	9	+++*	+++	+++	+++	$ 0.80	$ 7.20
Carbon disulphide	21	++	+	+++	—	.15	3.15
Ethylene dichloride	34	++	?	+++	—	.07	2.38
Methyl bromide	3.6	+++	?	+++	?	.65	2.34
Tetrachlorethane	46	+++	?	?	+++	.19	8.74
Pentachlorethane	46	+++	?	?	?	.20	9.20

*+++ represents high killing power, ++ moderate, and + low effectiveness.

Table 11 lists the fumigants considered in this bulletin, their range of practical effectiveness in pest control (indicated by + signs), and the approximate cost per thousand square feet of soil surface.

PRACTICAL USES FOR SOIL FUMIGATION

Seed beds, hot beds and cold frames. Disease-free seedlings for field planting are very important. Fumigation is probably the most efficient and economical method for adequate sterilization of seed-bed soils.

Nursery plant beds. Profit from nursery plants often depends upon freedom from nematodes and other pests. Soil fumigation can be used advantageously in the nursery plant bed, the cutting bench, and the nursery row.

Home flower and vegetable gardens. Because home flower and vegetable gardens usually are limited in size and location, it is often important to eliminate nematodes and other pests from the soil. The cost of treatment is often a minor factor. Soil fumigation is probably the most practical means of eliminating soil-borne injurious organisms in home gardens.

Commercial flower and vegetable gardens. Considerable work in vegetable gardens in the eastern states has shown substantial profits from soil fumigation with chloropicrin.

Orchards. Efficient spot treatments, which enable shrubs or trees to get a good start, may make the difference between fair plants or none in new plantings of peaches, figs, papayas, or other nematode-susceptible trees in root-knot areas.

Greenhouse benches. The cost of soil renewal and replacement, involving the movement by hand of tons of soil is one of the main cost items in the greenhouse culture of plants. Proper fumigation of greenhouse soils should eliminate completely the need for the removal of the soil, leaving only the maintenance of adequate organic material, acidity and fertility to keep plants in good condtion.

Greenhouse potting soils. Fumigation of potting soil is believed by the writers to be one of the most widely useful forms of soil sterilization. With proper equipment it is simple and inexpensive (Figures 8 and 9).

GENERAL DIRECTIONS FOR SOIL FUMIGATION

Ground plots. For seed beds, nursery plant beds, nursery rows, or for home or commercial flower and vegetable gardens, use soil fumigation only when the soil is fairly dry, uniformly loose, free from lumps and undecayed roots of a previous infested crop, and preferably when the temperature is 70° F. or warmer. Insert the chemical at recommended dosages, at points approximately twelve inches apart and quickly apply a means of sealing the gas into the soil. After four days remove covers and cultivate if necessary to accelerate gas elimination. Plant in the soil only after the odor of gas has completely disappeared. Details of the methods have been given in the descriptions of experiments.

Greenhouse benches. Use methods as for ground plots, governing dosages by the volume of soil to be treated. Methods should be adapted to the bench construction. All cracks in the bottom of the bench as well as the edges of the covering material should be sealed to prevent escape of the

gas. Some modification of standard bench construction may contribute to best fumigation-gas confinement.

Greenhouse potting soils. Use only airtight containers and apply dosages in accordance with cubic-foot contents. For small operations several large garbage cans or barrels capable of being completely sealed would be adequate equipment. In the containers illustrated, glue-coated paper was used for sealing. After the chemical is injected preferably at levels not greater than twelve inches apart, the covering material is glued tightly into place. Canner's label-lap-end paste is an excellent, quick drying adhesive for this purpose. French tape may also be used on smooth surfaces. Tying covers with a wire or a string does not provide sufficient sealing.

For large amounts of soil, one or more especially built boxes like the one shown in Figure 9 would be desirable. Such boxes must be airtight in construction. The box shown was built of center match flooring with a liberal application of carpenters' glue between the boards. Specifications for a two-cubic-yard box will be furnished upon request to the Lower

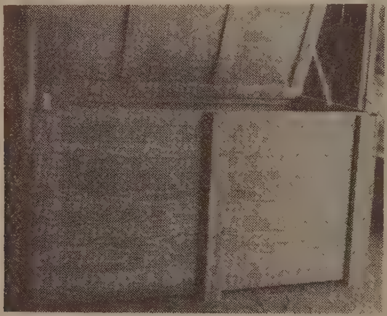

Figure 9. A soil fumigation box of two cubic yards capacity, with gas-impervious lid. The lid is made to rest upon cleats within the box, so that strips of adhesive paper tape will readily seal the outside edges.

Rio Grande Valley Experiment Station, Weslaco, Texas. For operators who use from one to several cubic yards of soil a day, a number of such boxes would be required. While one box is being used a second could be undergoing fumigation, and a third could be ærating. Precautions must be observed if this method is followed. For winter use a warm room adjacent to the head house and just back of the potting bench would be desirable. Boxes could be dumped by block and tackle to hasten gas elimination following treatment. Ventilation fans may be desirable when the soil boxes are in an enclosed room.

PRECAUTIONS

Although precautions in handling soil fumigants vary with the different chemicals used, certain general precautions are advisable for all materials.

General Precautions

Avoid spilling the chemicals needlessly. Use a funnel for pouring liquid fumigants from one container to another, or into applicators. In outdoor work, keep containers at arms length, and work on the windward side of the chemical. For all indoor applications requiring more than a minute or two, it is advisable to use the gas mask prescribed by the manufacturer for the particular fumigant used.

Use commercial applicators whenever the extent of operations justifies the cost. Wash applicators thoroughly after use with gasoline or kerosene to remove all traces of the chemical. Remove the washing material by ejecting it as in regular use. Finally operate the machine with motor oil, leaving a portion of it in the apparatus to keep the valve gaskets soft and in working order.

Specific precautions

Carbon disulphide is highly inflammable and explosive when mixed with air. All possible contact with sparks or open flames should be avoided. Breathing the gas momentarily is not dangerous.

Chloropicrin is highly toxic but is non-explosive. It has been used as a war gas but it is not dangerous when ordinary precautions are taken, as no one can willingly remain in a room with more than a small fraction of a dangerous concentration. A concentration as low as seven parts per million in the air will cause smarting and watering of the eyes. A deep breath will produce violent coughing, but a deep breathing of pure air afterward will bring quick relief. Repeated exposure to the gas for several days in succession is to be avoided, for injurious effects are cumulative and have been known to be fatal. In confined places such as greenhouses, a gas mask must be worn. Chloropicrin is injurious to living plants in very low concentrations. All plants must be removed from a greenhouse even if only a portion of the soil in the house is to be fumigated with this chemical. When the gas is being used outside, every care should be taken to avoid the possibility of leakage of the gas into a greenhouse with valuable plants. Soil fumigation with chloropicrin kills the beneficial nodule-forming bacteria *(Rhizobium sp.)*, so if sweetpeas, lupines, or other legumes are to be planted, the seed or soil should be inoculated with the proper nitrogen-fixing bacteria.

Ethylene dichloride has an odor and physiological effects like chloroform. Prolonged exposure to the fumes should be avoided. It is non-inflammable.

Methyl bromide is toxic to people, but there is little danger if ordinary precautions are taken against breathing the fumes. For indoor use, a gas mask should be worn. Because of its low boiling point, methyl bromide evaporates immediately upon exposure to open air at ordinary

temperatures. It is well to become thoroughly familiar with the directions provided by the manufacturers before fumigating with this chemical.

PHYSICAL PROPERTIES OF SOIL FUMIGANTS

The important physical properties of the leading fumigants discussed in this bulletin are recorded in Table 12. The figures for vapor pressure

Table 12. Physical properties of soil fumigants.

Chemical	Specific gravity as a liquid	Weight per gal.—lbs.*	Boiling point °C.	Vapor pressure 20°C.	Vapor pressure 25°C.	Specific gravity of gas (air = 1)
Carbon disulphide	1.256†	10.48	46.2	297.5	361.0	2.8
Chloropicrin	1.67†	14.00	112.0	18.2	24.0	5.7
Ethylene dichloride	1.257†	10.53	83.5	60.4	77.1	3.5
Methyl bromide	1.732‡	14.47	4.5	1315.0	1824.0	3.3
Pentachlorethane	1.681†	14.03	160.5	3.0	4.0	7.0
Tetrachlorethane	1.596†	13.32	146.3	5.1	6.8	5.8

*1 gallon of water weighs 8.34 pounds.
†At 20° C.
‡At 0° C.

are of particular interest in that they (together with molecular weights) constitute a measure of the penetrating power of the gases. Carbon disulphide and methyl bromide, for example, have greater vapor pressures and lower molecular weights than chloropicrin and, if adequately confined, their powers of penetration are very great. The low vapor pressure and high molecular weight of pentachlorethane explain its delay in evaporating from the soil.

DOSAGES AND CONVERSION FIGURES

For the convenience of the operator, Table 13 gives the correct figures for converting standard dosages per cubic foot into cubic yard figures (for the treatment of potting soils); and into rates per thousand square feet and per acre for ground-plot application. Where nursery rows or crop-plant soil are to be treated in the row only, leaving the middles untreated as is done with pineapples (23, 33, 34), the acre rate is reduced in proportion to the area actually treated. The formula given by Young (72) can be adapted to other chemicals as well as chloropicrin and carbon disulphide. In fumigating with chloropicrin, it is well to remember that 3 milliliters of chloropicrin per square foot of soil equals 480 pounds per acre. Similar general formulæ can be developed for other fumigants. For determining the rate of application of limited amounts of a chemical, the pounds of fumigant per acre multiplied by the conversion constant, 0.023, equals approximately the number of pounds of fumigant necessary for 1000 square feet of soil (Table 13).

Table 13. Dosages of soil fumigants.

Chemical	Milliliters per*		Pounds per	
	Cubic foot	Cubic yard	Thousand square feet	Acre foot
Chloropicrin	2	54	7.4	320
"	2.5	67	9.2	400
"	3	81	11.0	480
"	4	108	14.7	640
Carbon disulphide	8.3	224	23.0	1000
Ethylene dichloride	11.6	313	32.0	1400
Methyl bromide	1	27	3.8	166
Pentachlorethane	12.4	335	46.0	2000
Tetrachlorethane	13	350	46.0	2000

*1 milliliter (ml.) = about 20 drops; 30 ml. = 1 liquid ounce; 1 ml. = 1 cubic centimeter (c.c.). A teaspoon holds about 5 ml.

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